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Modelling of pool stratification and mixing induced by steam injection through blowdown pipes

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ABSTRACT

Containment overpressure is prevented in a Boiling Water Reactor (BWR) by condensing steam into the pressure suppression pool. Steam condensation is a source of heat and momentum. Competition between these sources results in thermal stratification or mixing of the pool. The interplay between the sources is determined by the condensation regime, steam mass flow rate and pool dimensions. Thermal stratification is a safety issue since it limits the condensing capacity of the pool and leads to higher containment pressures in comparison to a completely mixed pool with the same average temperature. The Effective Heat Source (EHS) and Effective Momentum Source (EMS) models were previously developed for predicting the macroscopic effect of steam injection and direct contact condensation phenomena on the development of stratification and mixing in the pool. The models provide the effective heat and momentum sources, depending on the condensation regimes. In this work we present further development of the EHS/EMS models and their implementation in the GOTHIC code for the analysis of steam injection into containment drywell and venting into the wetwell through the blowdown pipes. Based on the PPOOLEX experiments performed in Lappeenranta University of Technology (LUT), correlations are derived to estimate the steam condensation regime and effective heat and momentum sources as functions of the pool and steam injection conditions. The focus is on the low steam mass flux regimes with complete condensation inside the blowdown pipe or chugging. Validation of the developed methods was carried out against the PPOOLEX MIX-04 and MIX-06 tests, which showed a very good agreement between experimental and simulation data on the pool temperature distribution and containment pressure.

1. Introduction

The Pressure Suppression Pool (PSP) of a Boiling Water Reactor (BWR) is designed to protect the containment from overpressure by condensing the steam released from the primary circuit. In a BWR, steam can be injected to the PSP from the drywell and primary circuit though blowdown pipes and spargers (Pershagen, 1994). For instance, in case of Loss-Of-Coolant Accident (LOCA), steam released from the primary system through a break is pushed into the PSP through blowdown pipes and can be condensed if water in the pool is subcooled. The pool is also a source of water for emergency core cooling system (ECCS). A similar system, known as the In-containment Refueling Water Storage Tank (IRWST), is also found in advanced Pressurized Water Reactors (PWRs) such as the AP1000 and APR1400.

Direct condensation of steam injected into a water pool is as a source of heat and momentum. Competition between these sources determines whether the pool is thermally stratified or mixed (Li and Kudinov, 2010; Li et al., 2014a). The condensation regimes play important role in the competition. For example, in the regime of complete steam condensation inside a blowdown pipe, the latent heat is deposited in the water layer above the pipe outlet. Water below the pipe outlet remains cold. The small momentum induced by the flow of condensed liquid at the pipe outlet can be insufficient to overcome buoyancy forces that support the stability of the hot layer (Li and Kudinov, 2010; Li et al., 2014a; Laine et al., 2013). Condensation in other regimes (e.g. chugging, oscillatory bubbles, and stable jets) can create larger momentum sources, and lead to development of a large scale circulation in the pool which can break or erode the stratified layer (Laine et al., 2013).

The development of thermal stratification in the PSP is an issue of safety significance. Steam condensation is very limited if the water temperature at the pipe outlet is close to saturation, even

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if bottom layer of the pool remains cold. Thus, stratification limits steam condensation capacity of the pool. Moreover, the pool surface temperature determines the steam partial pressure in the containment gas space. Higher surface temperatures of a stratified pool will lead to higher containment pressure compared to a completely mixed pool, at the same average pool temperature. For instance, the containment pressure was rapidly increasing at Fukushima Daiichi Unit 3 during first 12 hours of the operation of the Reactor Core Isolation Condenser (RCIC) (Mizokami et al., 2013, 2016). When the pressure reached 400 kPa, the automatic protection system had to shut down the RCIC, leaving the plant without core makeup water. Based on a mixed pool assumption, lumped parameter codes under-estimated the maximum pressure by about 160 kPa (Mizokami et al., 2013, 2016). A benchmark study presented by Pellegrini et al. (2016) shows that the pressure can be well predicted when assuming thermal stratification in the wetwell pool. This assumption was used by most of the participating agents of the benchmark. Good agreement was also observed by some participants when assuming a leak from the drywell into the suppression chamber. However, the fact that the activation of the spray caused a decrease in the pressure suggests that that thermal stratification and mixing are the most likely reasons for the observed pressure behavior.

The goal of this paper is to build a model capable of predicting the pool behavior and its effect on the containment pressure during a prototypic LOCA type accident. Modeling of direct steam condensation phenomena is a challenge for contemporary codes. While CFD is too computationally expensive (Tanskanen et al., 2014; Patel et al., 2017; Pellegrini and Naitoh, 2016), lumped and 1D codes are inadequate for prediction of 3D, transient mixing phenomena (Li and Kudinov, 2010; Li et al., 2014a). Moreover, numerical oscillations of the flow may occur in case of direct modeling of steam injection into a pool, and can cause artificial mixing of the pool (Li and Kudinov, 2010). In general, state-of-the-art approaches cannot capture the effect of different condensation regimes due to the lack of the physical models. For instance, containment codes such as GOTHIC (Ozdemir and George, 2015), and other thermal hydraulic codes (e.g. RELAP5 RELAP5/MOD3.3 Code Manual Volume IV, 2006), do not have a model for predicting the effect of a steam blowdown into a pool. Available condensation models are mostly designed for pipe flow regimes such as bubbly, churn, film, etc. Thus, mixing transients where the steam-water interface is displaced outside the pipe (chugging, oscillatory bubble, etc.), cannot be predicted by the code. As a result, original GOTHIC models are limited to stable stratification transients where all steam condenses inside the pipe (Ozdemir and George, 2015).

In order to develop predictive capabilities for thermal stratification and mixing induced by steam injection into a pool, Li and Kudinov (2010) introduced the concept of Effective Heat Source (EHS) and Effective Momentum Source (EMS) models, which was further developed and validated in a series of publications (Li et al., 2014a,b,c; Gallego-Marcos et al., 2016a,b,c; Villanueva et al., 2015). The main idea of the effective models is that, to predict the global pool behavior, direct contact condensation phenomena occurring at the small temporal and spatial scales do not need to be resolved. Instead, it is the time-averaged Effective Heat (EHS) and Momentum (EMS) Sources transferred from the steam to the large scale pool circulation what needs to be modelled. The approach has been developed and validated for condensation regimes of chugging and complete condensation inside the blowdown pipe (Li et al., 2014b), and are currently under development for the oscillatory bubble regimes appearing in spargers (Gallego-Marcos et al., 2016a,b). The data for validation was obtained in scaled experiments performed in the PPOOLEX facility in LUT (Laine et al., 2015), and the PANDA facility at PSI (Kapulla et al., 2015).

Previous implementation of the EHS/EMS models (Li et al., 2014b; Gallego-Marcos et al., 2016a,d) was based on experimental data on the steam condensation regime in the blowdown pipe, which allowed the calibration of the models. Steam injection into the drywell and the feedback between pool conditions and containment pressure were beyond the scope of the analysis reported in Li et al. (2014b), Gallego-Marcos et al. (2016a,d). However, for plant applications, the condensation regime has to be predicted by the code based on the steam injection flow characteristics, determined by the feedback between the drywell and wetwell.

In this work, we present the implementation the EHS/EMS models in GOTHIC 8.1(QA) capable of simulating the drywell and wetwell pool behavior during LOCA type conditions. One of the major problems for the implementation of the model were the numerical oscillation that occur when the steam injected from the drywell to the wetwell is condensed. To resolve the issue, the numerical oscillations were time-averaged during run-time to enable the estimation of the steam flow rate. This time-averaged flow was then used as an input for the EHS/EMS models, which used it to select the condensation regime and effective heat and momentum sources. The containment thermal-hydraulic code GOTHIC was chosen as the simulation platform since it integrates CFD capabilities (Navier-Stokes solver with two-equation turbulence models) with engineering equipment such as pumps, heat exchangers, valves, etc. (GOTHIC Thermal Hydraulic Analysis Package, 2014).

The paper is organized as follows: Section 2 presents the EHS/EMS models for blowdown pipes, and Section 3 their implementation in GOTHIC. A validation of the models against the PPOOLEX MIX-04 and MIX-06 experiments is presented in Section 4.

2. EHS/EMS models for blowdown pipes

The EHS/EMS models compute the effective heat Q_{eff} and momentum M_{eff} sources induced by the steam injection using Eqs. (1) and (2) respectively (Li et al., 2014a),

$$Q_{eff}(t) = \frac{1}{\Delta t}\int_{t-\Delta t}^{t} Q(\tau)d\tau \tag{1}$$

$$M_{eff}(t) = \frac{1}{\Delta t}\int_{t-\Delta t}^{t} M(\tau)d\tau \tag{2}$$

where the integrals represent the time-average of the instantaneous variations of the sources over a period Δt of time. These variations are due to the oscillatory nature of direct contact condensation. For example, the large scale motions of the liquid inside the pipe during the chugging regime, the small scale oscillatory bubble behavior, etc. In this section, we focus on the regimes of chugging and complete condensation inside the pipe. Section 2.1 presents the correlations used to predict the effective momentum induced by chugging, and Section 2.2 the correlations used to predict the transition between these two regimes.

2.1. EMS correlations for chugging regime

Chugging is a condensation regime characterized by a periodic motion of the steam-water interface inside the blowdown pipe. This motion is driven by the pressure changes induced by the growth and collapse of large steam bubbles. To analyze the effect of chugging on a thermally stratified pool, 12 experiments were performed in the PPOOLEX facility under the MIX series (Laine et al., 2013). The PPOOLEX facility, located at Lappeenranta University of Technology (LUT), Finland, was designed to represent the containment of Olkiluoto BWR plant in a 1:320 vol scale. It consists of a cylindrical stainless steel vessel divided into a 13.3 m^3 drywell and a 17.8 m^3 wetwell. In the MIX series, steam was injected into